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322. ERF valves controlled by plane capacitor electric field

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Abstract. Holes filled with electrorheological fluid (ERF) are used to form the Braille symbols or relief in Array Manipulators. Matrix of holes is made in the fabric-based copper laminate. Voltage applied to coppered upper and lower surfaces of the plate creates electric field, which controls ERF viscosity. Three methods to form a relief are investigated: (a) using an elastic membrane, covering the holes, (b) dielectric pins moving in the holes, (c) metallic pins moving in the holes. Electric field in a hole of the matrix was calculated as electric field in a hole of plane capacitor. In the case of metallic pins, the mean electric field near the electrodes is considerably stronger than in the case of dielectric pins. The controlling voltage can be decreased using multilayer copper laminate valves, composed of some fabric-based plates with opposite directions of electric field in neighbouring plates.
Keywords: electrorheological fluid ERF, valve controlled by electric field, multilayer valve, Braille reader.

Introduction

Industrial interest in ERF and research in prototype and model devices over two last decades has seen considerable growth [1, 2]. ERF technology controls the transfer of mechanical energy in an increasing number of applications. There are three possible modes of operation for electrorheological fluids: squeeze, shear and valve [3, 4]. All these modes can be used for matrix manipulator formation. Perspective application of ERF matrix manipulator is palpation as part of medical diagnosis. The shear operation mode of electrorheological fluids is used in this case [4]. Other actual application of ERF matrix manipulators is Braille reader. The relief of Braille letters must be fixed. The valves as elements of matrix are used in this case. The graphic display with electrorheological valves was patented in 1991 [5]. ERF valve in this display is completely open or closed. When electric field is connected, it dramatically changes electrorheological characteristics (viscosity, shear, stresses etc.) of ERF and the valve closes. The ERF valves can be used to shape Braille letters or relief of other graphic objects. The problem of ERF valves (see [3-9]) is mounting of electrodes. Usually, uniform electric field is created in a hole with ERF. One of controlling electrodes is mounted along the axis of the hole, the other – on the wall of the hole, or – both electrodes on the inner wall of the hole. Accuracy in mounting the system of electrodes and sliding elements into holes is of paramount importance. When the number of valves is high (10 000 and more, e.g. in array manipulators or 2D Braille devices) accuracy presents a serious technological problem. Other problem is connection electrodes of valves to voltage source.

We propose to use for valve matrix realization standard laminated electronics plate. It allows to simplify considerably the manufacturing of electrodes needed for electric field creation, its electrical connection to voltage source and valves control.

Design of the matrix of holes

Standard electronics circuit plate is coppered on both sides. When a hole matrix is made in the coppered plate, upper and lower copper surfaces serve as electrodes of electric field in the holes.

To control voltage of every hole discretely, individual electrodes on the plates are made in a form of strips, with an angle of 90 degrees (Fig. 1) between them on both sides of the plate. This design ensures that voltage is in only one hole when voltage between one strip on the upper side and one strip on the lower side is applied. The width of the electrode strip is δ = 2mm; the gap between electrodes is Δ = 0.5mm. These dimensions correspond to distances between pins of classical Braille devices.

Three different modes of ERF valves design with laminate electronics plate can be realised. There are valves with a wide hole, with a hole with dielectric pin and with a hole with metallic pin (see Fig. 2). The graphic relief is formed on elastic film, which covers holes. The rig is formed by pressure pulse, when the valve is open. A fragment of graphic display is shown in Fig. 3. The laminate electronics plate 1 with hole matrix covers the reservoir 2 with ERF. By laminate strips 3 the voltage can be connected to holes. To the holes 4 voltage is applied (the valves are closed), to the holes 5 voltage is not applied (the valves are open).

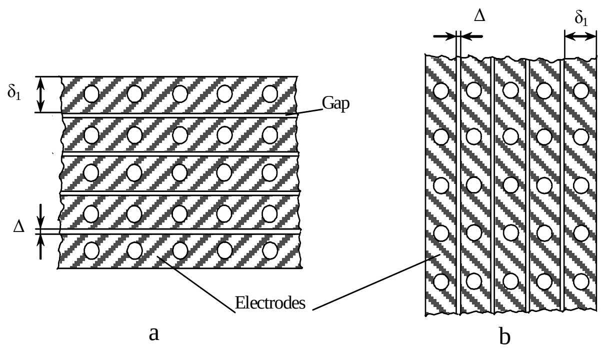

Fig.1. Formation of electrodes on upper (a) and lower (b) copper surfaces

The average value of electric field strength in the part of hole with ERF is important for choice of valve type. The electric field distribution in a wide hole was investigated in [10, 11]. For the case of fabric-based plate with relative permittivity ε_{II}=7 it can be expressed this way [11]:

$$E_r = K_1[1-K_2 y_s^2]\cdot[1+K_3 r_s^2]\cdot[1+K_4 r_s^2 y_s^4], \qquad (1)$$

where relative value of electric field strength is $E_r = E/E_0$, E - electric field strength in any point of hole, $E_0 = U/d$, $U=V_0-(-V_0)$ is the control voltage applied to plate laminate surfaces, d – is the plate thickness. Coefficients K_1 – K_4 depend on relative permittivity ε_I of ERF:

$$K_1 = K_1(\varepsilon_I) = \frac{1{,}03\varepsilon_I}{0{,}027\varepsilon_I^2 + 1{,}29\varepsilon_I - 0{,}12}, \qquad (2)$$

$$K_2 = K_2(\varepsilon_I) = \frac{0{,}893\varepsilon_I - 0{,}04}{0{,}912\varepsilon_I + 1}, \qquad (3)$$

$$K_3 = K_3(\varepsilon_I) = \frac{\varepsilon_I}{2{,}96\varepsilon_I + 1{,}77}, \qquad (4)$$

$$K_4 = K_4(\varepsilon_I) = \frac{2{,}25\varepsilon_I - 1}{0{,}247\varepsilon_I + 1{,}61}. \qquad (5)$$

The view of electric flux lines across a valve volume is shown in Fig. 2, a. The electric flux lines density is proportional to electric field strength. In the central part of hole (Fig. 2, a) the field strength is considerably lesser than near hole wall. When we have the valve with dielectric pin and its permittivity is similar to ERF permittivity, the field distribution near pin is the same, as in periphery of hole without pin. The average field value in valve part with ERF is more than in entire hole volume. Therefore, the valve with dielectric pin will be closed by lesser control voltage than valve without pin.

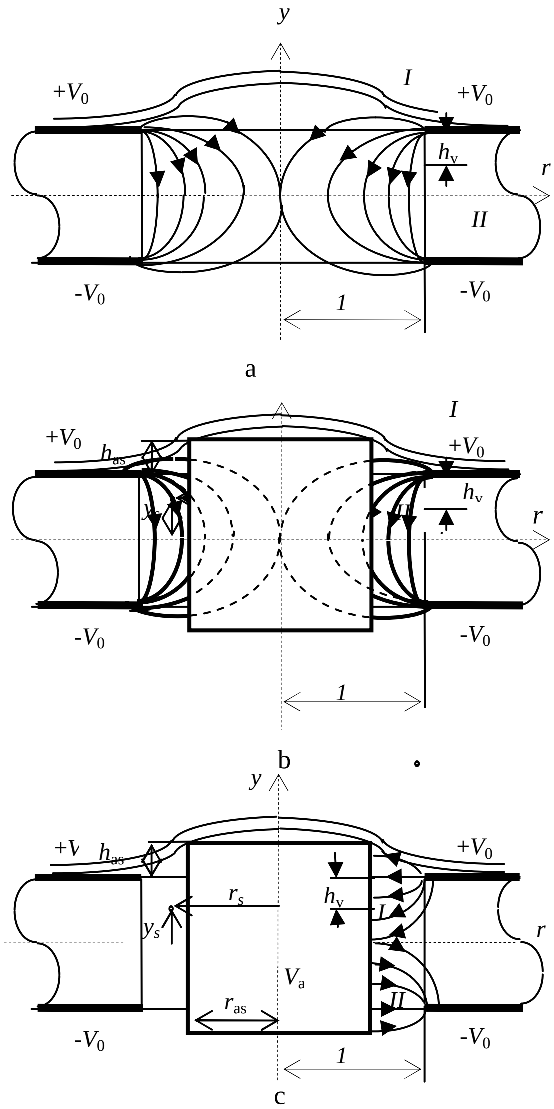

Fig. 2. The design of ERF valves on the base of standard laminated electronics plate: a – without pin, b – with dielectric pin, c – with metallic pin

The electric potential of any point of metallic pin volume is the same. The electric flux lines are perpendicular to pin surface. They are distributed, as it is shown in Fig. 2, c (supposing, that the pin potential is V_a=0). The electric field strength E can be expressed approximately as ratio of applied voltage U to length l_l of electric flux line $E=U/l_l$. The potential of middle line parallel to plate electrodes is equal to zero. We can see, comparing the pictures in Fig. 2, b and c, that the distance at plate with potential $+V_a$ or with potential $-V_0$ to surface with potential V=0 is lesser when the metallic pins are used.

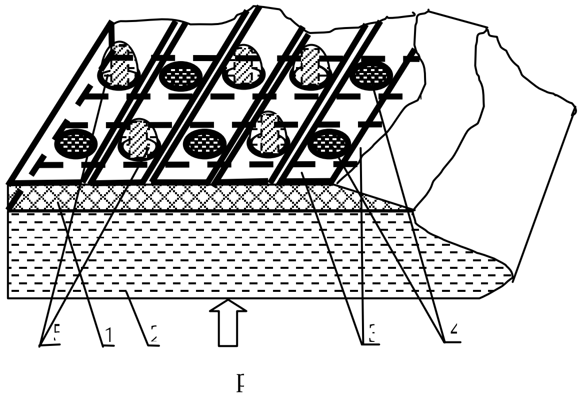

Fig. 3. The view of some part of graphic display

The electric field of ERF valve hole fabricated in laminate electronics plate was modelled using program package COSMOSM. The distribution of field was compared among the three different valve designs shown in Fig. 2, a, b and c. The metallic pin potential V_a is not fixed. So the field in valve with metallic pin was modelled for three different cases, when V_a=0, 200V and 400V, and the average value of field was computed. The minimal average field value was obtained, when V_a=0. The modelling was made for five different values of ERF permittivity ε=1, ε=2.4, ε=3.8, ε=5 and ε=7. The obtained results are summarized in Fig. 4. There are presented the average values of relative electric field strength $\overline{E}_r$. The relative electric field strength $E_r = E/E_0$ is computed dividing obtained field value E by electric field strength inside electronics plate: $E_0=U/d$. For the hole with metallic pin the average value of electric field strength was computed in the electrode zone, when relative distance at electrode plane is not more than 0,25. The results, when V_a=0, are presented in Fig. 4. We can see that the average field in the hole near the metallic pin is considerably major than near the dielectric pins or in the hole without pin.

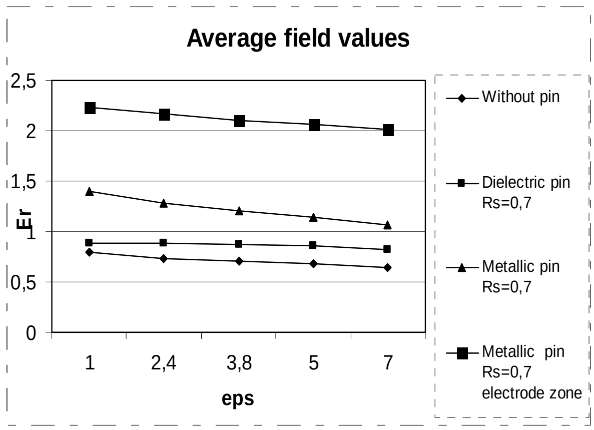

Fig. 4. Dependence of average values of electric field strength E_r upon ERF permittivity (eps) when R_s=0,7 is relative radius of the pin

The average relative electric field E_r in ERF is ≈1,7 times stronger using metallic pin and ≈1,25 times stronger using dielectric pin than in the hole without pin. For the points, a distance of which from electrode plane is not more than 0,25 (electrode zone), average field strength in hole near metallic pin is ≈1,75 stronger than in all volume near metallic pin.

The ERF with low permittivity must be used for the electric field increasing.

Multilayer valves

When voltage between the electrodes increases, stiffening of ERF begins on the plane of electrodes. Height h_f of stiff ERF layer is needed to fix the pin reliably. This height can be obtained in different ways: it can be increased by raising electrode voltage or by forming a hole in multilayer plate, e.g. stiff layer h_s develops when voltage between electrodes of any plate is U_s.

Total height h_f of stiff ERF layer, when the number of plates with the same voltage U_s between neighbouring plates is n-1 plates, can be obtained (where n=E{h_f/h_s} (E{…} – whole part of the number), if the directions of voltage in neighbouring plates is opposite.

The design of valve is presented in Fig. 5. The 1 and 2 are thin plastic plates, guiding the pin in vertical direction, the lower plate 2 is perforated to pass ERF into valve hole, 3 – the pin, 4 – some layers of laminate plates, 5 – reservoir with ERF, 6 – the lower wall of reservoir, 7 – thin elastic film, preventing the ERF leak.

We can see from Fig. 4, that the average value of electric field strength is especially large in electrode zone.

The medium with a permittivity more than 1 is above and below inner electrodes in multilayer valves. Therefore, the field at inner electrodes is stronger than the field at upper and lower electrodes, where the field is pushed out of ERF into the area where relative permittivity is 1. There is additional motivation to use multilayer valves.

For example, stiff layer height h_s of one layer of the multilayer plate is calculated for valve with five layers when height needed to fix the pin reliably is h_f=0,5h. The package composed of five layers contains six electrodes. Therefore, each stiff layer height is $h_s=h_f/6=0{,}083h$. Mean electric field of the layer with height h_s= 0,083h is close to $\overline{E}_{\max}$. Electric field $\overline{E}_{\max}$ depends on relative pin radius $\overline{E}_{\max} = \overline{E}_{\max}(r_{as})$. When the height of standard plates is 2h=1mm and voltage between electrodes is U, the basic value of electric field is $E_0=U/2h=U$ V/mm. $\overline{E}_{\max}(r_{as})$ can be expressed this way [10]:

$$\overline{E}_{\max}(r_{as}) = \overline{E}^{s}_{\max} E_0 = \frac{h}{r_0}\frac{1}{1-r_{as}}U\,. \qquad (6)$$

When the diameter of the hole is 1 mm, h/r_0=1. Typical value of electric field for ERF to stiffen is $\overline{E} \cong 1$ kV/mm [12]. Substituting $\overline{E} \cong 1$ kV/mm into (1) for

$\overline{E}_{\max}(r_{as})$, reliable pin fixing voltage U_s is obtained in the interval 100÷300V, when r_{as} varies in the interval 0,7÷0,9. When h and r_0 are lower this voltage is lower as well.

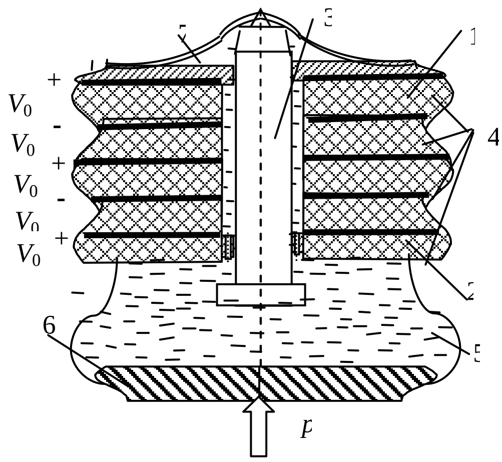

Fig. 5. The design of multilayer valve

A feasible design of valves matrix with metallic pins was implemented in EU ITACTI project (IST – 2001 – 32240 ITACTI "Smart Interactive Tactile Device Effecting Graphical Display for the Visually Impaired"). To control cavity pressure the lower cavity wall was made elastic. The volume of the cavity was controlled by piezoelectric plate fixed to walls.

Experiments with the model developed for EU ITACTI project showed, that the vertical force was of the order of 0,5 N and corresponded with the forces of typical Braille devices. When this force is applied, fixing of the pin was achieved due to control voltage U_c≈250V in monolayer valve. With multilayer valves this voltage can be decreased. Time response of valves was of the 1-5 ms order.

A Braille device operator has no contact with this voltage. In the case of the damage of device the maximal current of control voltage source is not more than 1 mA and can not cause any harm to the operator (Directive 2004/40/EC of the European parliament and of the Council).

Conclusions

ERF valves are used to shape Braille symbols or relief of other graphic objects. Any relief can be formed by an adequate number (from hundreds to thousands) of holes. ERF valves are holes filled with ERF, viscosity of which is controlled by electric field. The matrix of holes can be made in both surfaces of copper laminated fabric plate. Electric field is created connecting voltage to both, upper and lower, copper surfaces.

Relief is formed on membrane using pin or without it. When the same control voltage is used, the average electric field in ERF is ≈1,7 times stronger using metallic pin and ≈1,25 times stronger using dielectric pin than in the hole without pin.

Electric field strength increases when ERF permittivity decreases and relative pin radius increases. The control voltage can be decreased using multilayer valves. The design of multilayer valve is proposed.

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